Coupled Receiver-Decoders*

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Abstract

This paper describes coupled receiver-decoder architectures for suppressed carrier convolutionally-coded signals and residual carrier turbo-coded signals. Using total required transmit power as a metric, these new schemes perform 2.8 to 3.8 dB better than uncoupled systems when the signals are impaired by phase noise and AWGN typical of a deep space link. These gains arise because the coupled systems wipe partially decoded data from the signal without resorting to squaring.

1 Introduction

In modern coded coherent communications systems, the tasks of carrier recovery and data decoding are accomplished in an *isolated* manner. The sole communication between the receiver and decoder is via a sequence of soft symbols sent from the receiver to the decoder. Typically, carrier recovery is accomplished by a loop motivated by the Maximum A Posteriori (MAP) estimate (e.g., the Costas loop), and the decoder may also produce the MAP estimate of decoder bits (e.g., the Viterbi algorithm). However, the optimality of a phase tracking loop is based on the assumption that transmitted symbols are independent, and the optimality of a Viterbi decoder is based on the assumption of perfect carrier recovery. Neither assumption holds for coded, phase noisy signals.

In contrast, we propose a *coupled* receiver and decoder, in which information transfer is bidirectional: the decoder output helps refine the carrier recovery, and the receiver output helps refine data decoding. For convolutional codes, we propose jointly estimating the carrier phase and data bits. For turbo codes, we propose explicit feedback between separate receiver and decoder blocks after each iteration of the decoder. These methods allow adequate carrier recovery and data detection on very phase noisy signals, even when the carrier is fully suppressed.

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2 Preliminaries

2.1 Signal Model

This paper considers a single channel binary signal with a residual carrier and data subcarrier. This type of signaling is commonly used with the Block V Receiver (BVR) [Kin96, Yue83] and has the form

$$r(t) = \sqrt{2P_t}\sin\left(2\pi f_c t + \theta_c(t) + \beta \sum_{k=-\infty}^{\infty} c_k p(t - kT_{sym})\,\mathrm{sgn}(\sin(2\pi f_{sc} t))\right) + n(t), \tag{1}$$

where P_t is the transmitted power, f_c is the carrier frequency, $\theta_c(t)$ is the carrier phase noise with PSD proportional to $1/f^3$, β is the modulation index, c_k is a coded bit in $\{-1,+1\}$, $p(\cdot)$ is a rectangular pulse, T_{sym} is the coded symbol duration, f_{sc} is the data subcarrier frequency, and $n(t)$ is additive white Gaussian noise (AWGN) with one-sided PSD N_0.

After down-converting, sampling, and carrier mixing, we obtain a signal that can either be mixed with a subcarrier NCO and accumulated at the symbol rate to give the data signal $r_d[k] = \sqrt{P_d}c_k e^{j\theta_k} + n_k$, or low pass filtered and accumulated at the symbol rate to give the residual carrier signal $r_c[k] = \sqrt{P_c}e^{j\theta_k} + n'_k$, where $P_d = P_t\sin^2\beta$ is the data power, $P_c = P_t\cos^2\beta$ is the carrier power, $\theta_k = \theta_c(kT_{sym})$, and each component of the complex noise terms n_k and n'_k are i.i.d. with normal distribution $N(0, N_0/(2T_{sym}))$. We have assumed that subcarrier and timing losses are negligible.

2.2 The Uncoupled Receiver-Decoder

In an uncoupled, non-data-aided system, the receiver tracks the carrier from the residual carrier signal, and this is used to wipe off the phase noise in the data signal. This architecture is shown in Fig. 1. The

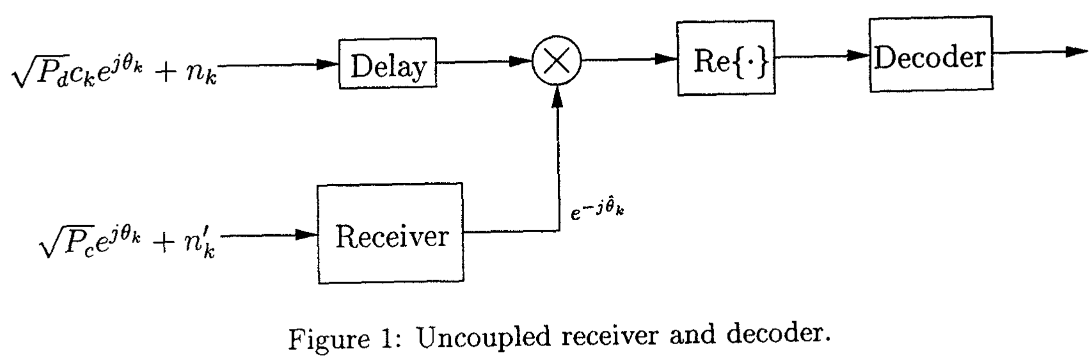

Figure 1: Uncoupled receiver and decoder.

communication is unidirectional, and no soft information from the decoder is used by the receiver.

3 Coupled Receiver-Decoders

3.1 Convolutional Codes, Suppressed Carrier

The joint receiver-decoder for convolutional codes is shown in Fig. 2. It uses per survivor processing phase tracking within a Viterbi decoder. At each state in the trellis, the Viterbi decoder stores an associated hypothesized data sequence according to the surviving path to that state, which is used to unmodulate the signal. If the hypothesized data sequence is the correct one, then the data-wiped signal is a CW signal with phase noise and AWGN, trackable by a PLL or other loop in the usual way. The phase estimate at each state requires no decoding delay, so updates from one trellis state to the next can track phases that vary somewhat rapidly.

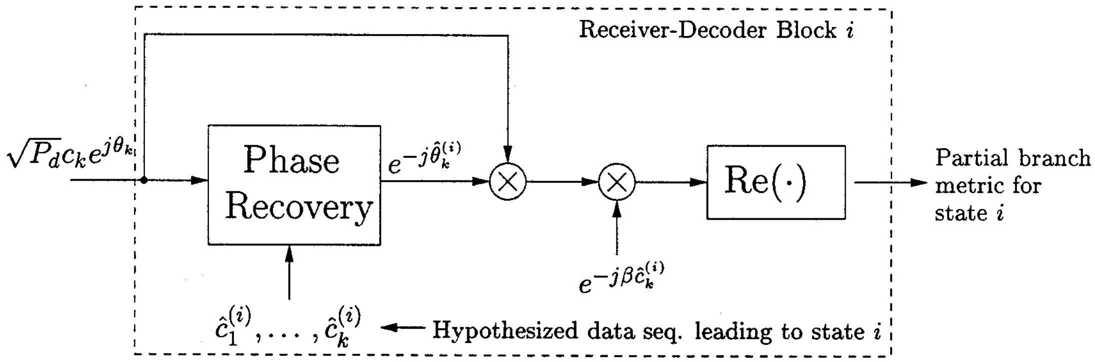

Figure 2: Joint receiver-decoder for convolutional codes, state i. There is such a block for each state in the trellis. Phase recovery uses the hypothesized data sequence leading to state i at time k.

This architecture was tested on a NASA standard rate 1/2, constraint length 7 convolutional code [Kin96, Pro95] at 40 bps, with a phase noise level of -10.58 dBrad^2/Hz at a 1 Hz offset, which is a signal of particular interest to NASA [Ham99]. Fig. 3 shows the BER performance vs. $P_t/(N_0 R_d)$ (equal to E_b/N_0 for suppressed carrier), which gives an apple-to-apple comparison across receiving architectures because each scheme does not use the same modulation index. The uncoupled system is based on a *residual* carrier signal with a modulation index optimized for best BER performance. As can be seen, the joint receiver-decoder saves 3 dB at a BER of 0.01.

3.2 Turbo Codes, Residual Carrier

The coupled receiver-decoder architecture is shown in Fig. 4. To begin, a Wiener filter tracks the residual carrier signal, wipes off the phase noise as best it can, and sends the result to the turbo

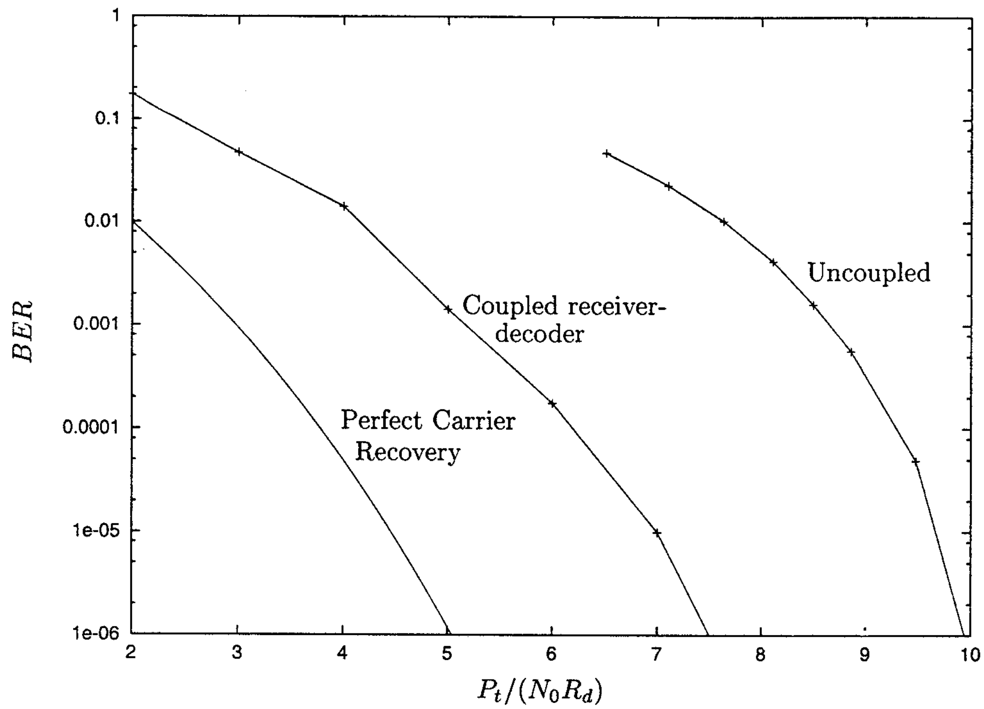

Figure 3: Comparison of coupled and uncoupled receiver-decoders for convolutional codes, suppressed carrier.

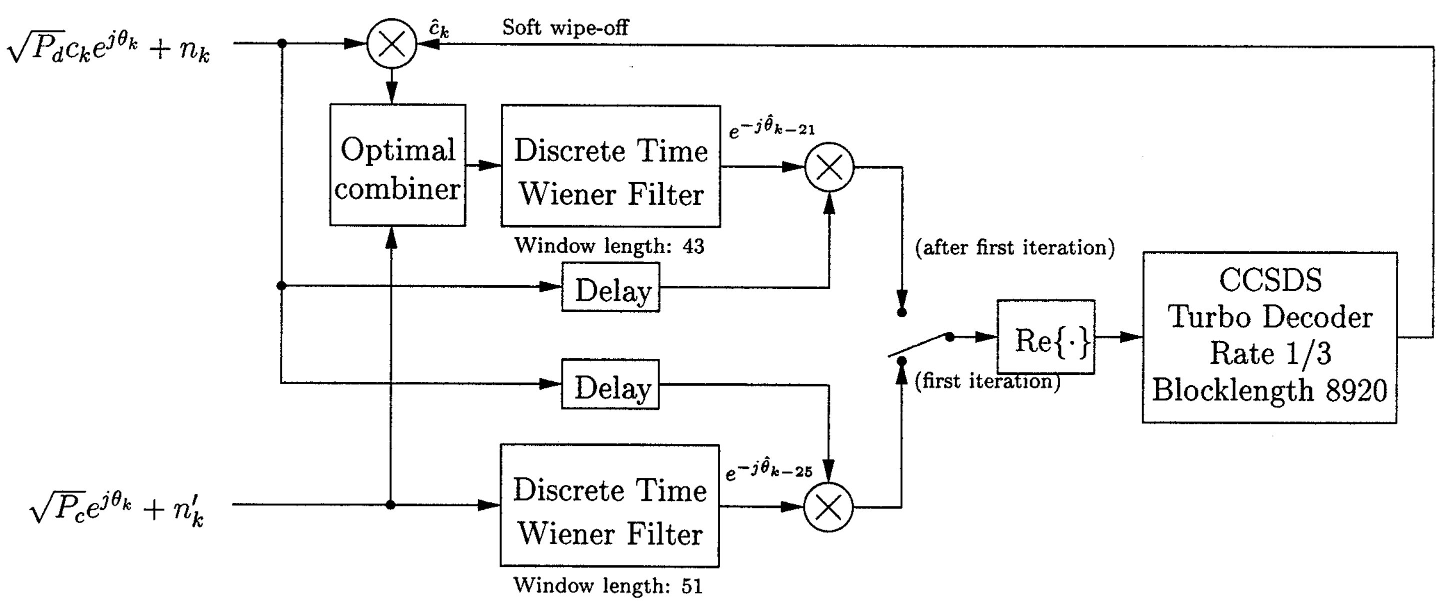

Figure 4: Coupled receiver-decoder for turbo codes, residual carrier.

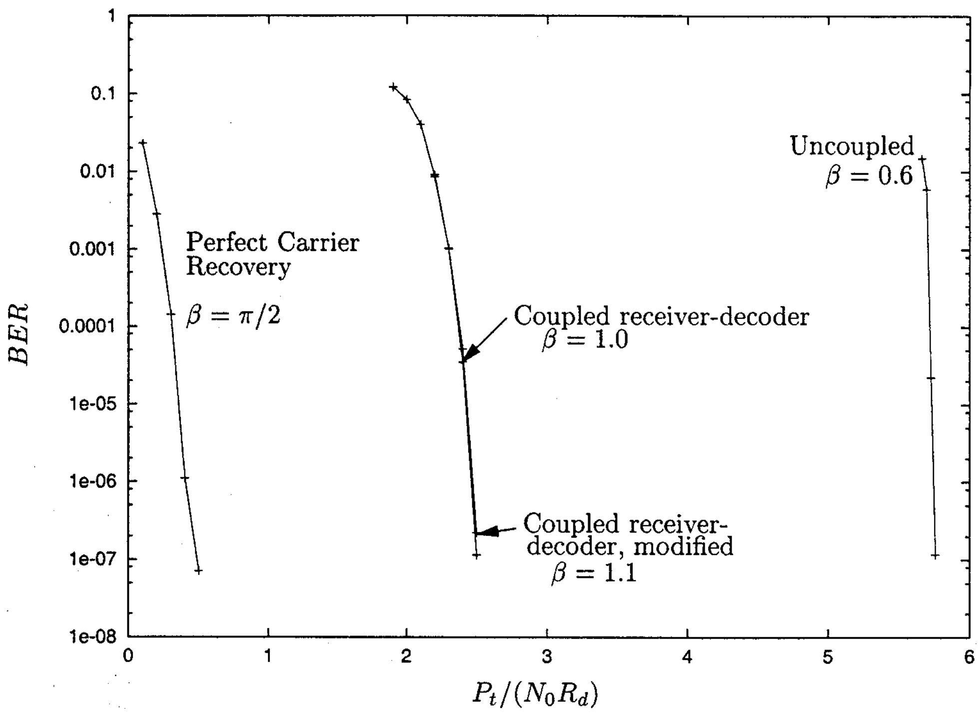

Figure 5: Comparison of coupled and uncoupled receiver-decoders for turbo codes, residual carrier.

decoder. The turbo decoder goes through its first iteration, and sends soft data symbols (real numbers) back to the receiver, where they are used to softly wipe off the data signal. For example, we might have $c_k = -1$ and the turbo decoder soft output may be $\hat{c}_k = -0.9$, which results in a soft wipe-off of $-0.9r_d[k] = 0.9e^{j\theta_k} + 0.9n_k$, a close approximation of a residual carrier signal. Once the data is wiped, the signal contains a large carrier phase component that can be combined with the residual carrier signal and tracked with another Wiener filter. The refined phase estimates from the Wiener filter are used to wipe the phase noise from the original, delayed data signal. The refined data samples are then sent back to the turbo decoder for the second iteration, and the process is repeated.

Fig. 5 shows the BER performance of the architecture on the same signal as above but with a rate 1/3 CCSDS standard turbo code [CCS99] replacing the convolutional code. The leftmost curve illustrates the nominal performance of the turbo code when perfect carrier reference is assumed, based on a suppressed carrier signal. At the other extreme, the rightmost curve illustrates the performance of an uncoupled system when phase noise is present. The modulation index was chosen to optimize BER performance while meeting current receiver requirements, using the method described in [Sha00]. This occured at approximately $\beta = 0.6$ radians. In between is the curve for the coupled receiver-decoder.

The modulation index was chosen to approximately optimize the BER performance. This was found to occur when $\beta \approx 1.0$ radians. The carrier tracking loss is about 2.0 dB, which represents a 3.75 dB improvement over the uncoupled architecture.

3.3 Modified Turbo Decoder, Residual Carrier

Another approach to the synchronization problem is to include the phase estimation in the turbo decoder. While full phase recovery might be a very complex task, a tuning-up of the coarsely estimated phase with a little help of turbo decoding is a viable option.

A phase estimate of the Wiener filter $\hat{\theta}_k$ is not perfect. The estimation error is approximately Gaussian distributed having relatively long tails which cause the largest decrease of the decoding performance. While it is rather difficult to assess the actual estimation error, the alternative solution is to concentrate it into the vicinity of zero, reducing the unwanted distribution tails. This can be done by rotating each complex symbol in opposite directions by $e^{\pm jE[|\theta_k - \hat{\theta}_k|]}$ (a value obtained either by analytical or empirical means) and processing the new streams of data by the modified turbo decoder.

The basic modification to the turbo decoder is the doubled number of states, which is necessary to process the doubled number of incoming symbols. Each trellis state is divided into a positive state and a negative state corresponding to the preceding transitions caused by symbol rotation of $e^{+jE[|\theta_k - \hat{\theta}_k|]}$ and $e^{-jE[|\theta_k - \hat{\theta}_k|]}$, respectively. Each of these states has four branches, as opposed to two in the classical BCJR algorithm, and the turbo decoding algorithm is essentially the same as in the classical version.

In Fig. 5, the performance of the the modified turbo decoder is shown to be nearly the same as the other coupled architecture, at an even higher modulation index, $\beta = 1.1$. A possible extension to include explicit feedback coupling may improve performance further.

4 Conclusions

This paper presented methods to couple receivers and decoders for phase noisy signals. The coupled receiver-decoders were simulated on low data rate signals, where phase noise becomes most problematic, and were found to save 2.8 to 3.8 dB in total transmit power over a simple uncoupled schemes with optimized modulation index.

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